



Jet Propulsion Laboratory
California Institute of Technology

The NASA Exoplanet Exploration Program: The Search for Planets, Habitability, and Life in our Galaxy

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January 19-21, 2015

**19th Annual International Conference on Gravitational Microlensing
Annapolis MD**



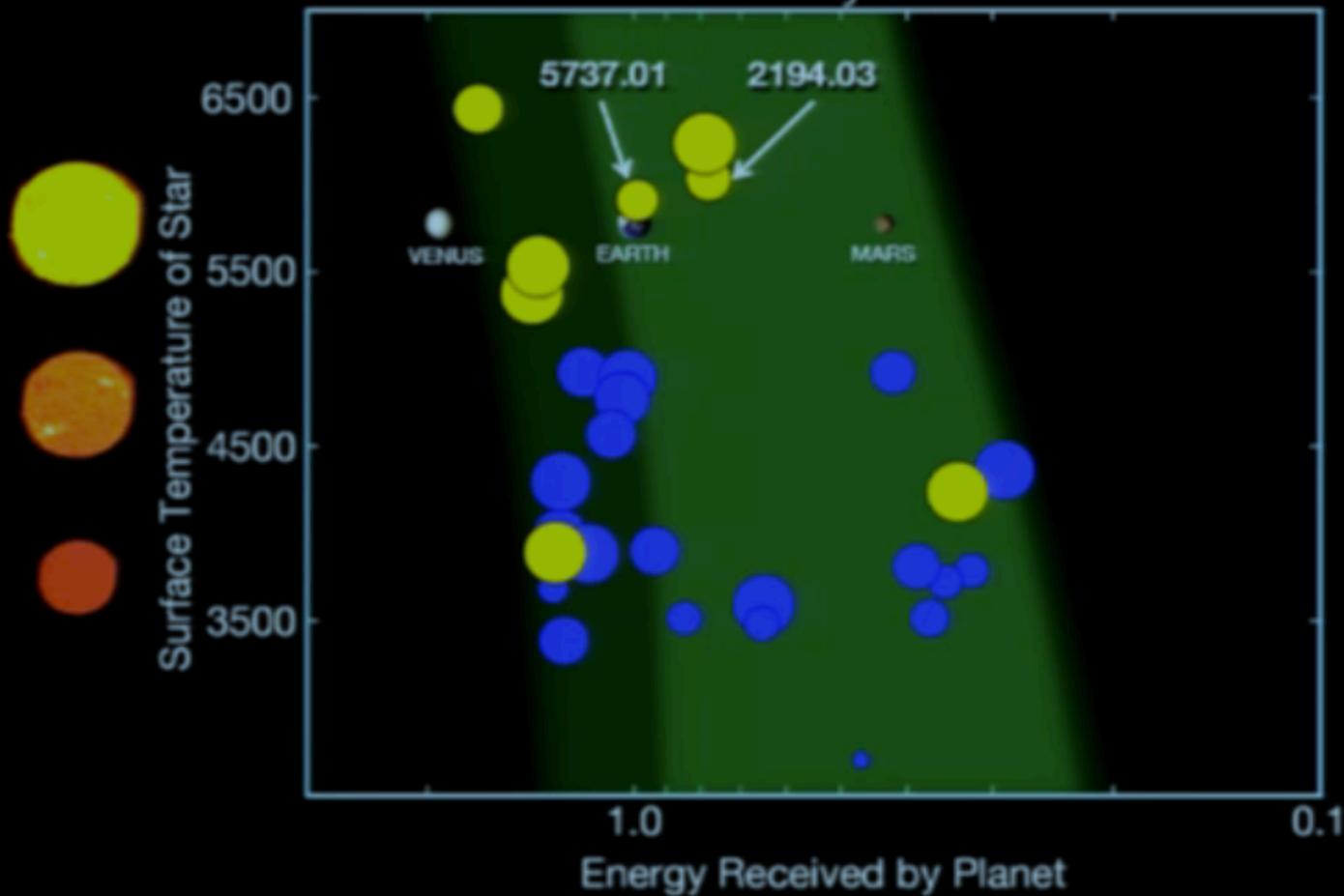
We are particularly interested in those in the *Habitable Zone*

Kepler

Eight New Small Candidates in the Habitable Zone



As of January 2015



Doug Caldwell, AAS 225 Meeting, Seattle, Jan 2015

Where will exploration take us in 100 years? Introducing the *Exoplanet Travel Bureau*

EXPERIENCE THE GRAVITY OF
HD 40307g A SUPER EARTH

The sixth exoplanet in its solar system, HD 40307 g is about twice the volume of Earth and eight times more massive, making it something in between a "Super-Earth" and a "Mini-Neptune." Planets in these categories were found in abundance by the Kepler mission, a surprising result that suggests our galaxy contains an abundance of small worlds. The "gray area" between Super-Earths and Mini-Neptunes isn't well understood at this point, so the planet itself may be terrestrial, as depicted here, or a more hostile world of gas and ice.

The Exoplanet Travel Bureau is a product of NASA's Exoplanet Exploration Program Office (www.planet.nasa.gov) located at NASA's Ames Research Center.

www.nasa.gov

RELAX ON
KEPLER 16b

THE LAND OF TWO SUNS

WHERE YOUR SHADOW ALWAYS HAS COMPANY

Like Luke Skywalker's home planet Tatooine in "Star Wars," Kepler 16 b orbits a pair of stars at a very close distance -- about 3 times farther from the center of the star pair than the stars are from each other. Depicted here as a terrestrial planet, Kepler 16 b might also be a gas giant like Saturn. Prospects for life on this unusual world aren't good, as it has a temperature similar to that of dry ice. But the discovery indicates that the movie's iconic double-sunset is anything but science fiction.

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Kepler-186f

WHERE THE GRASS IS ALWAYS REDDER ON THE OTHER SIDE

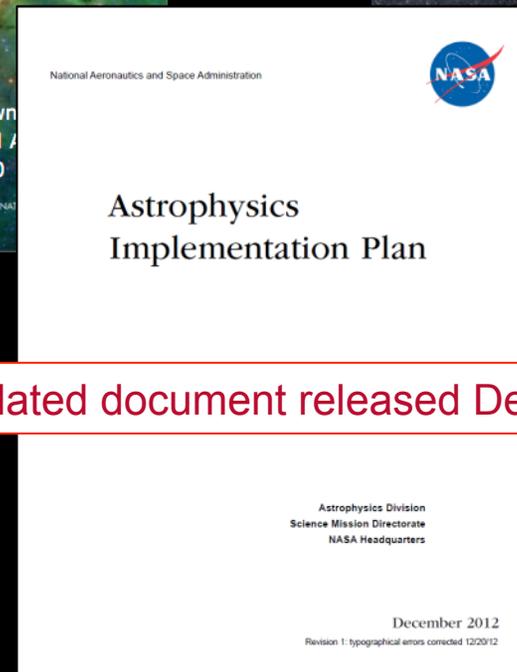
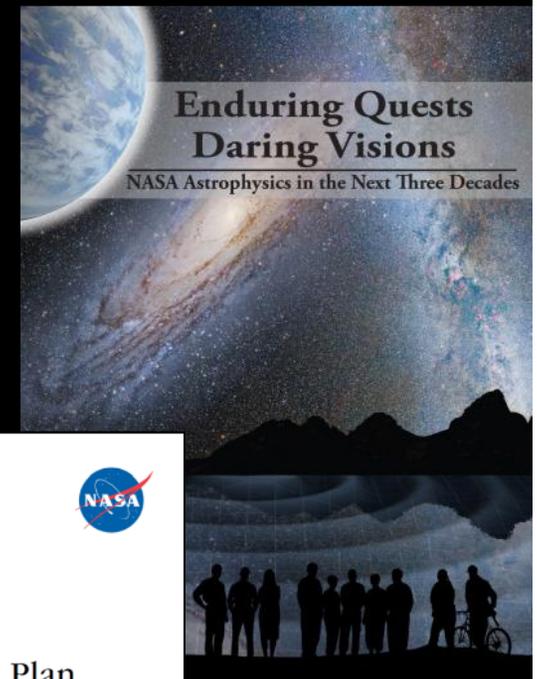
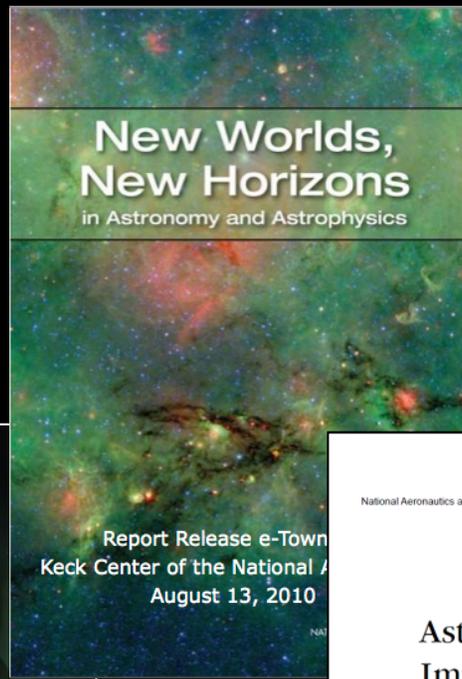
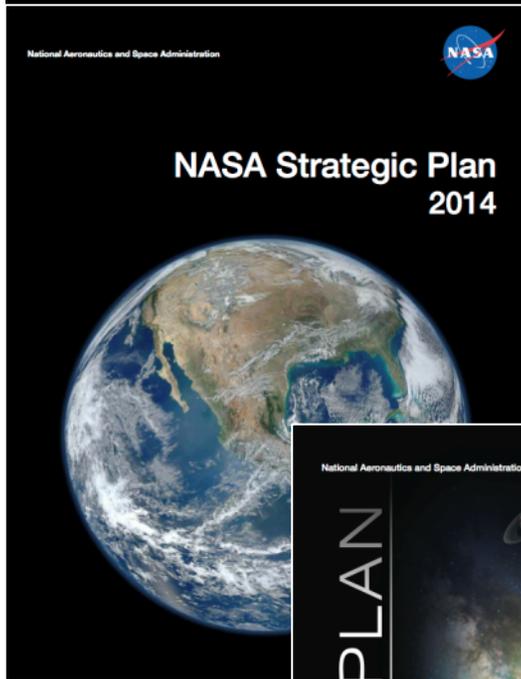
Kepler-186f is the first Earth-size planet discovered in the potentially habitable zone around another star, where liquid water could exist on the planet's surface. Its orbit is much closer and smaller than the orbit of Mars around the Sun, and the star is a red dwarf star, making for a cooler planet that's very different from the grass on Earth. This discovery was made by NASA's Kepler planet-finding space telescope.

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www.nasa.gov

The Exoplanet Exploration Program

NASA Astrophysics Documents



Updated document released Dec 2014

<http://science.nasa.gov/astrophysics/documents>

What is the Purpose of the Program?

Described in 2014 NASA Science Plan



Exoplanet Exploration Program

1. Discovering planets around other stars
2. Characterizing their properties
3. Identifying candidates that could harbor life

Interdisciplinary Studies of **Exoplanets:**

Crosscutting Work Between the Astrophysics
and Planetary Science Divisions

The Exoplanet Exploration Program

Space Missions and Mission Studies

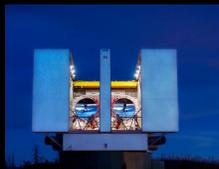


Public Engagement



Supporting Research & Technology

Key Sustaining Research



Large Binocular Telescope Interferometer



Keck Single Aperture Imaging and RV

Technology Development

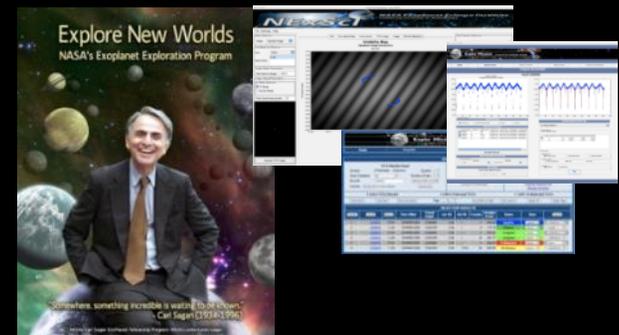


High Contrast Imaging



Deployable Star Shades

NASA Exoplanet Science Institute



The Program relies on the Scientific Community

Active teams and committees:

- **ExoTAC** (Technology Assessment Committee)
Chair: A. Boss, Carnegie Institution
- **WFIRST/AFTA SDT** (Science Definition Team)
Chair: D. Spergel, Princeton University
- **STDTs** (Science and Technology Definition Team)
One each for:
 - **Exo-C** (Probe Coronagraph) Chair: K. Stapelfeldt, GSFC
 - **Exo-S** (Probe Starshade) Chair: S. Seager, MIT
- **ExoPAG** (Program Analysis Group)
Chair: S. Gaudi, Ohio State University

Key Exoplanet Science Questions

1. Discovering Planets: How abundant are exoplanets in our Galaxy?

- Radial Velocity <math>< 1 \text{ m/s}</math>
- Transit Photometry <math>< 10 \text{ parts per million}</math>
- Microlensing Exoplanet populations and demographics

2. Characterizing Planets: What are the (large) exoplanets like?

- Transit Spectroscopy <math>< 100 \text{ parts per million}</math>
- Direct Imaging
 - High Contrast <math>< 1\text{E-}9</math> (after post-processing)
 - Small Inner Working Angle <math>< 500 \text{ mas}</math> (<math>< 200 \text{ mas}</math>)
 - Spectroscopy $R \sim 40$ in visible, near infrared (water lines)

3. “Pale Blue Dots”: Are the planets habitable? Are there signs of life?

- Transit Spectroscopy <math>< 1 \text{ part per million}</math>
- Direct Imaging
 - High Contrast <math>< 1\text{E-}10</math> (after post-processing)
 - Small Inner Working Angle <math>< 100 \text{ mas}</math> (<math>< 40 \text{ mas}</math>)
 - Spectroscopy $R \sim 70$ in visible, near infrared (biosignature gases)
 - η_{Earth} Quantify, for mission design
 - Exozodiacal Dust Quantify, for mission design
 - Yield Ideally: dozens of rocky planets

Current Exoplanet Science Missions

Kepler Space Telescope



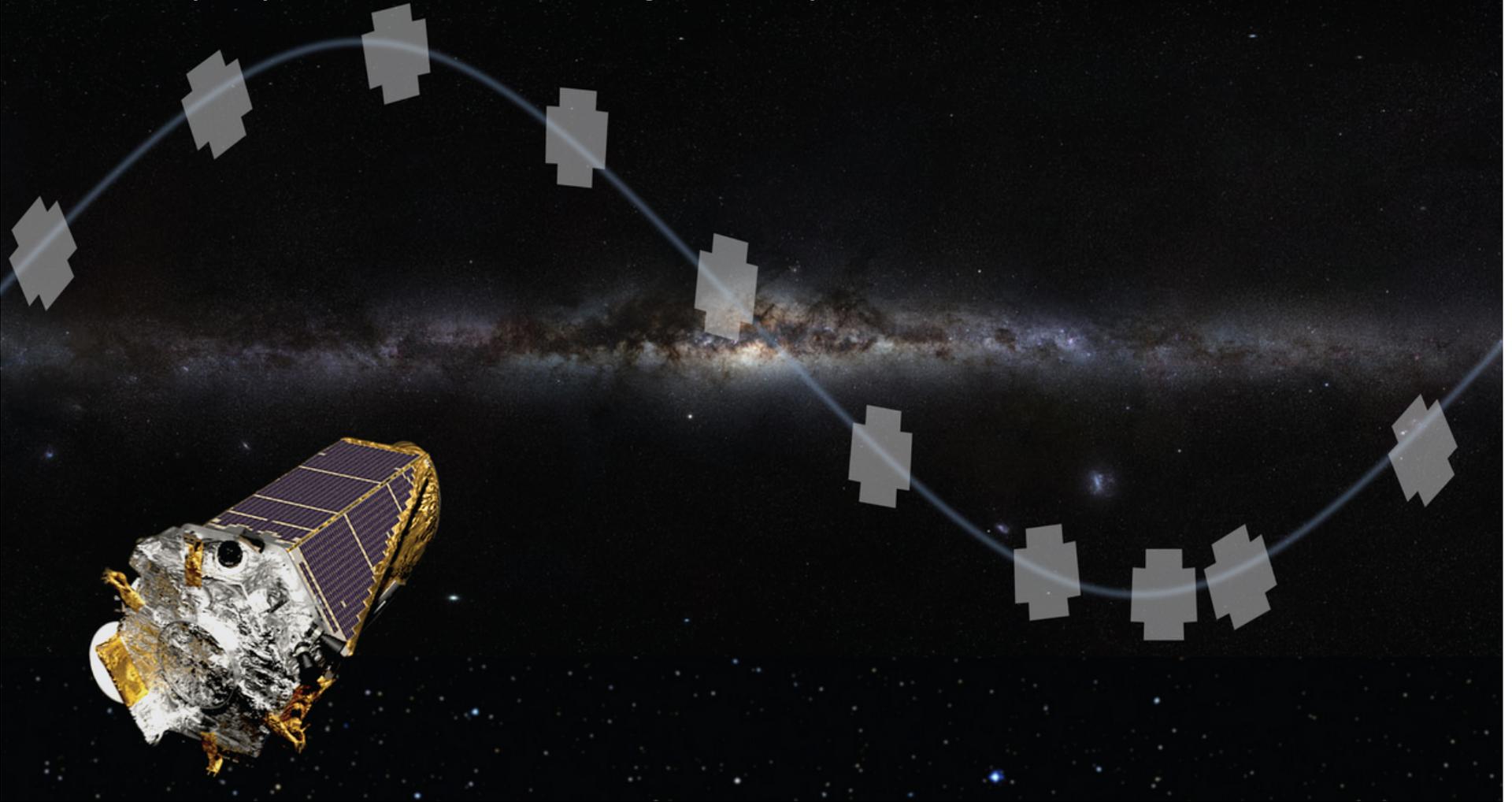
- **PI:** W. Borucki, NASA Ames Research Center
- **Launch Date:** March 6, 2009
- **Science Data Collection** through May 2013
- **Final processing of full data set** underway

Kepler Closeout

Harvesting the exoplanet yield from the mission

- Already available to Community: Q0-Q16
- Uniform Processing: Q0-Q17 (9.2)
 - Long cadence light curves Dec 2014
 - Short cadence light curves Mar 2015
 - Release notes Jul 2015
- Final Data processing: Q0-Q17 (9.3)
 - Light curves Jan 2016
 - Release notes Aug 2016

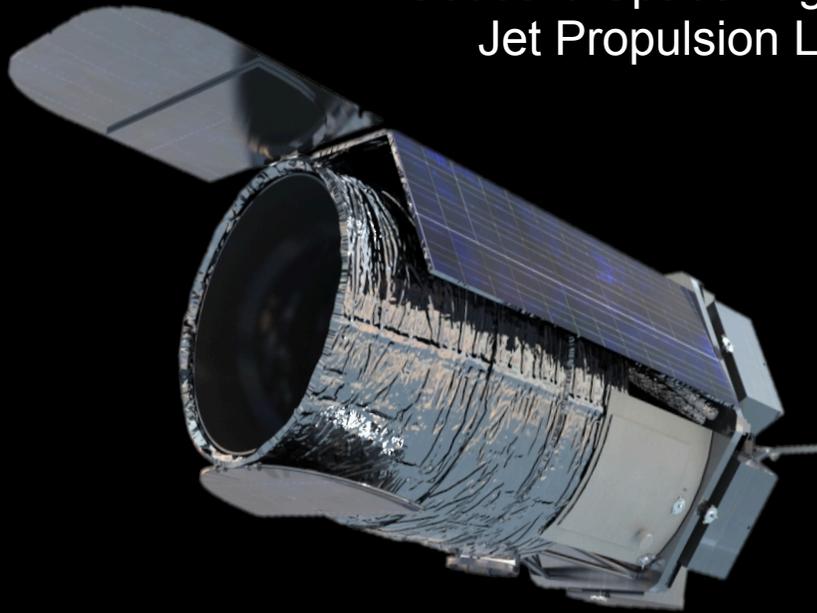
Kepler (K2) is now observing 80-day windows in the ecliptic



WFIRST / AFTA

Wide-Field Infrared Survey Telescope (WFIRST)
Astrophysics Focused Telescope Assets (AFTA)

Goddard Space Flight Center
Jet Propulsion Laboratory
STScI
NExScI



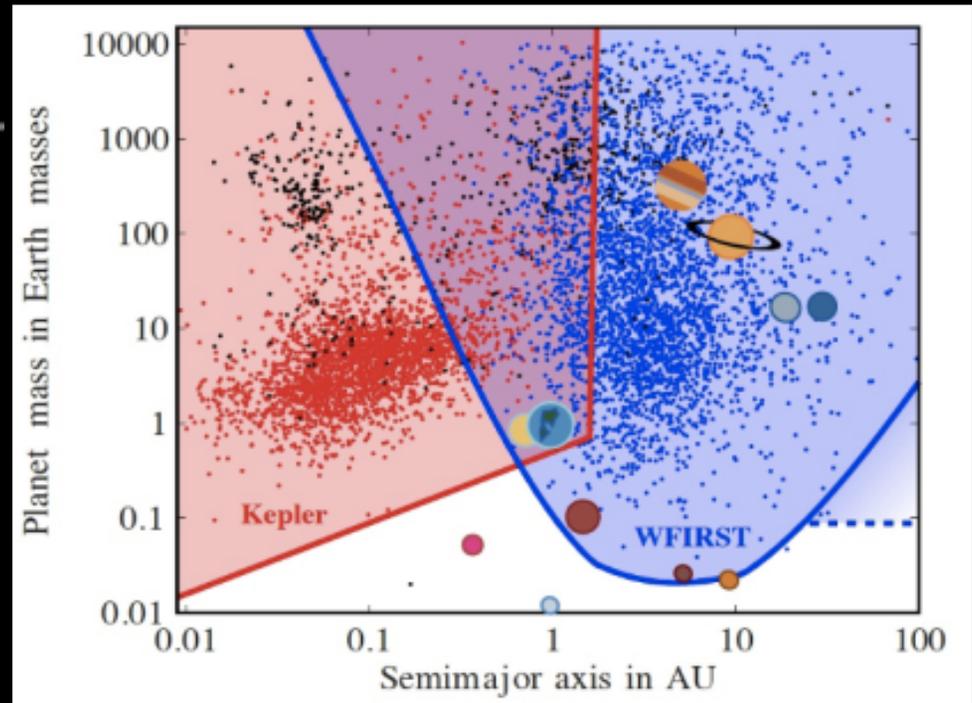
WFIRST / AFTA
Microlensing survey
completes the census
begun by Kepler

Wide-field Instrument

- H4RG detectors (Qty 18)
- Wavelength: 0.6 to 2.0 micron
- FOV: 0.28 deg²

Wide-field Instrument Science

- Dark Energy
- Infrared Survey
- Microlensing survey for exoplanets



WFIRST / AFTA Coronagraph

Direct Imaging of Exoplanet Nearest Neighbors



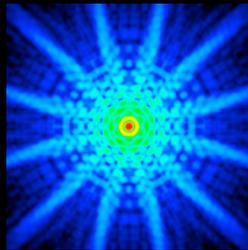
Coronagraph Instrument

- Imaging and spectra channels
- 0.4 – 1 μm bandpass
- $\leq 10^{-9}$ detection contrast
- 100 mas inner working angle at 0.4 μm
- $R \sim 70$

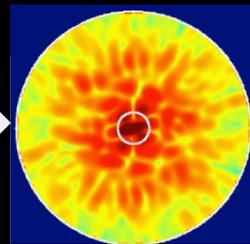
Coronagraph Science

- Imaging and spectroscopy of exoplanet atmospheres down to a few Earth masses
- Study populations of debris disks

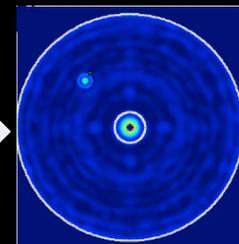
No Mask



With Mask

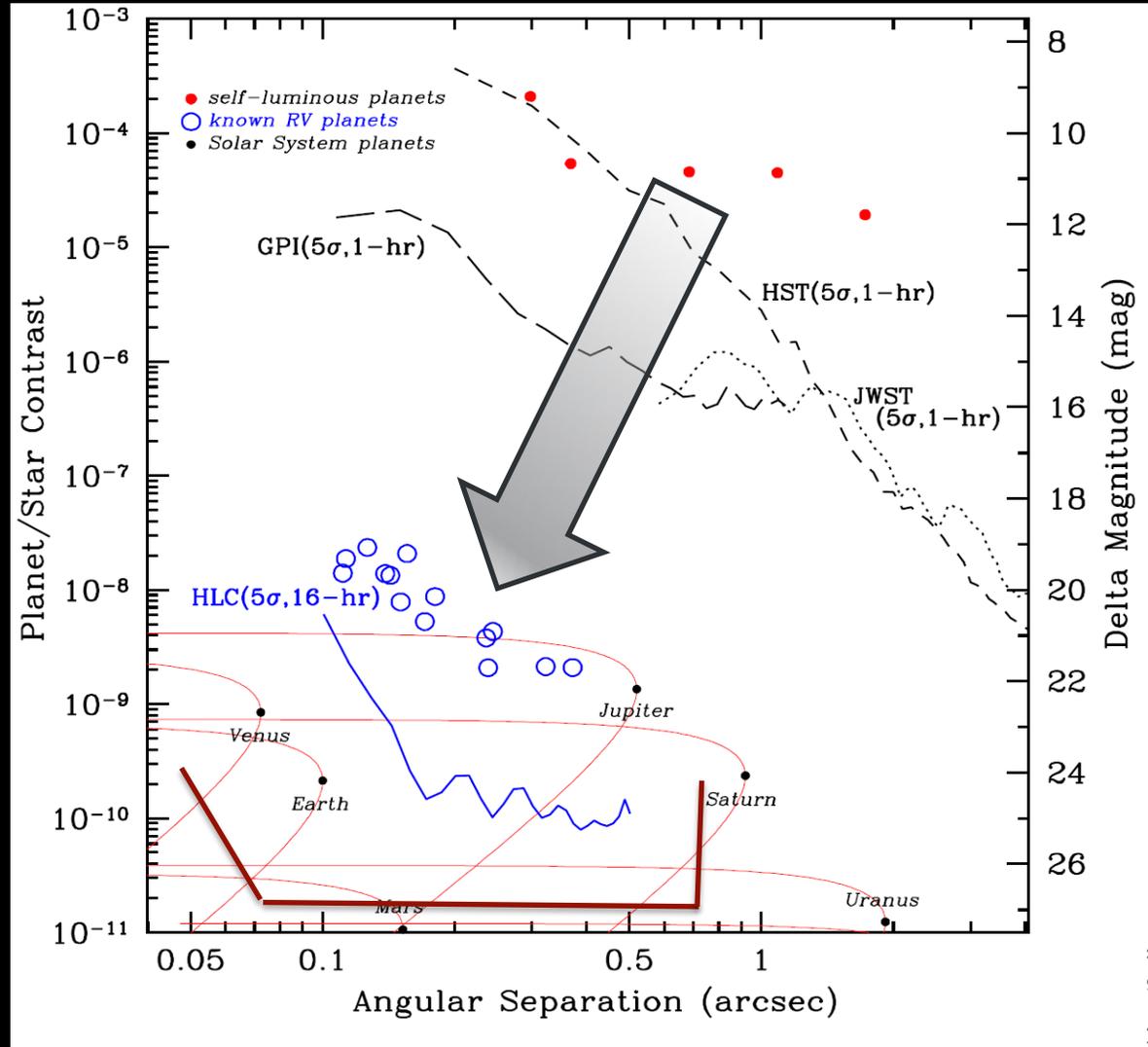


With Mask and Deformable Mirrors



Coronagraph will develop the technologies for a future exo-Earth mission

WFIRST Coronagraph images cool gas and ice giants



GPI

HST

JWST

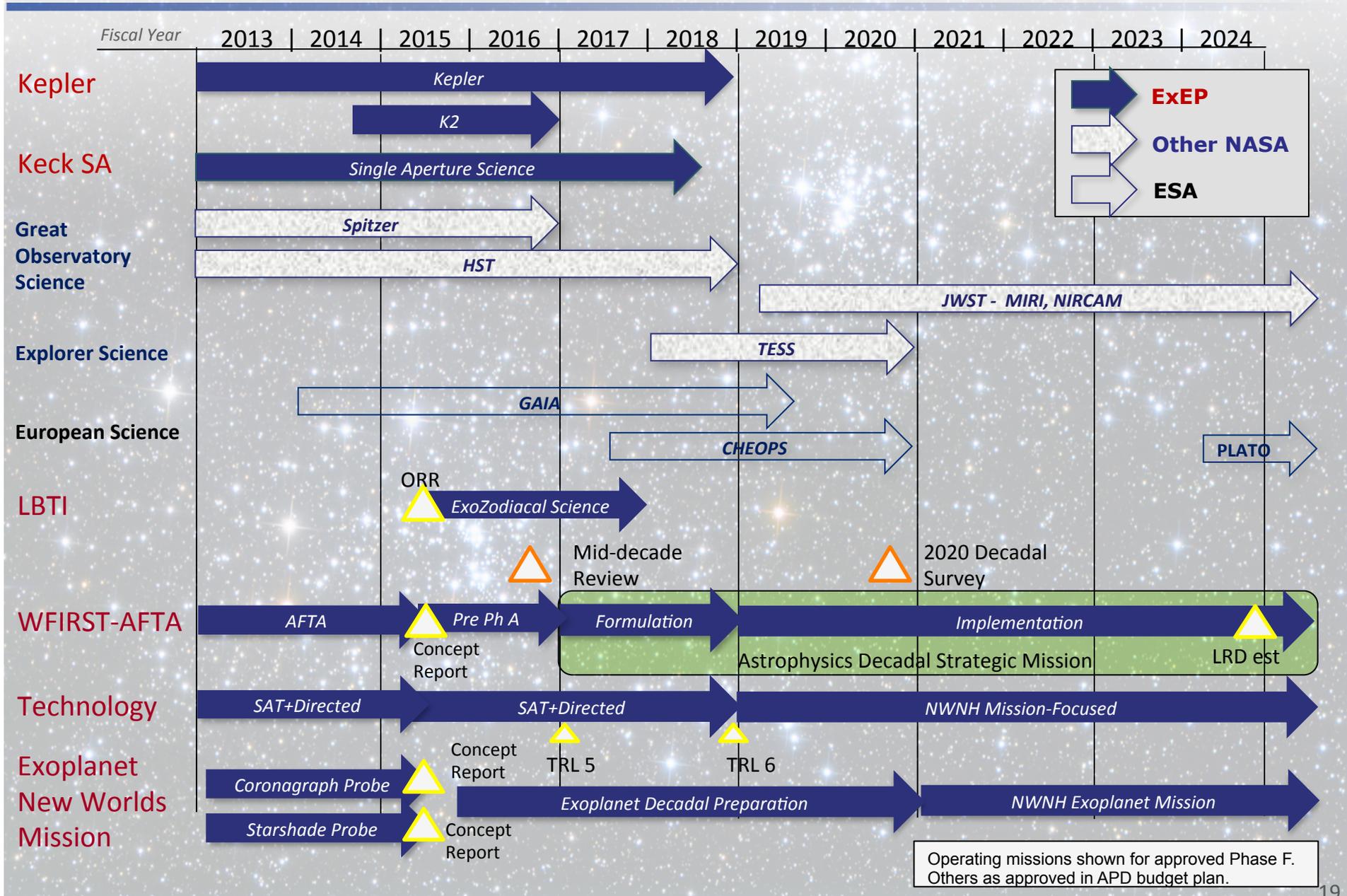
WFIRST

New Worlds
Telescope

W. Traub

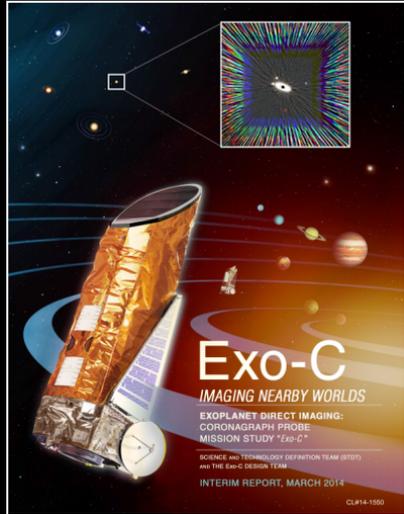
Exoplanet Exploration: A Decade Horizon

NASA and ESA efforts



Probe-Scale studies:

High-Contrast Imaging



Exo-C:

Internal Occulter
(Coronagraph)

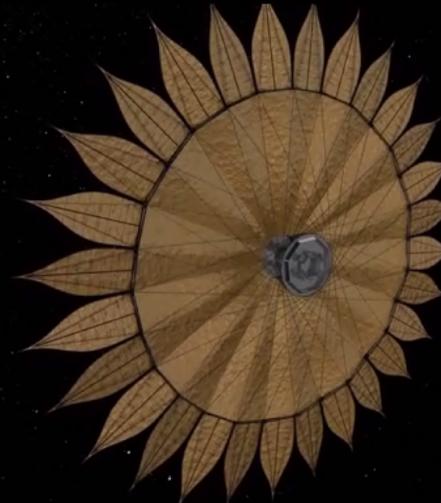
K. Stapelfeldt,
STDT Chair, GSFC



Exo-S:

External Occulter
(Starshade)

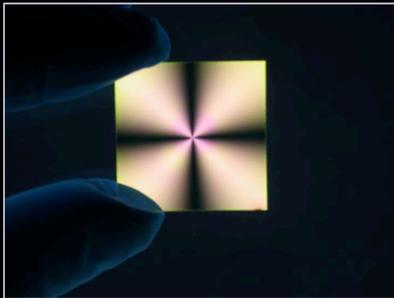
S. Seager,
STDT Chair, MIT



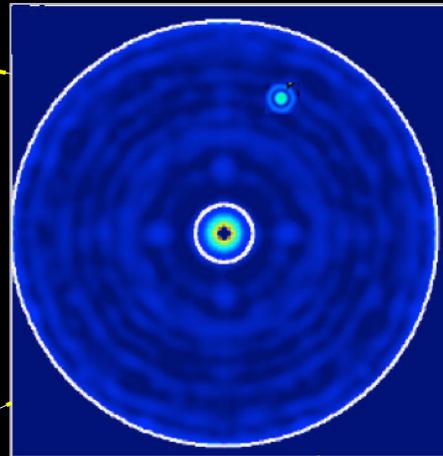
Enabling the Exo-Future: Technology Development

Technology Development for Coronagraphs

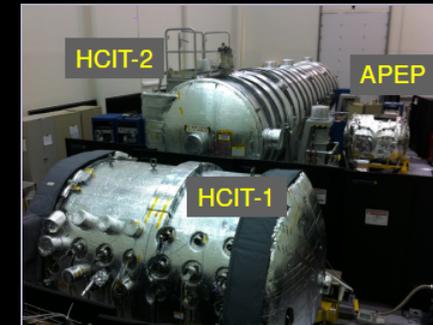
Occulting Masks/ Apodizers



Serabyn – Vector Vortex Mask

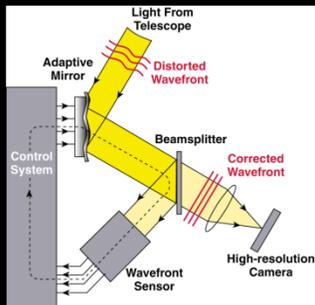


System Demonstration

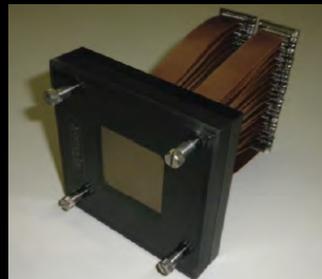


Jet Propulsion Laboratory

Low Order Wavefront Sensing and Control

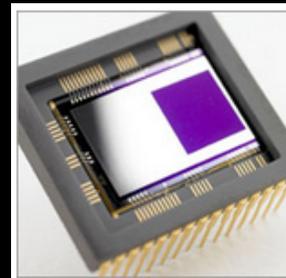


Deformable Mirrors



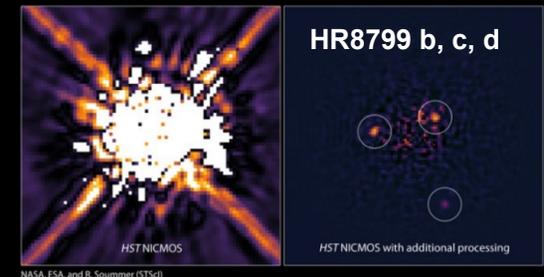
Xinetics

Ultra-Low-Noise Visible Detectors



e2v Electron Multiplying CCD

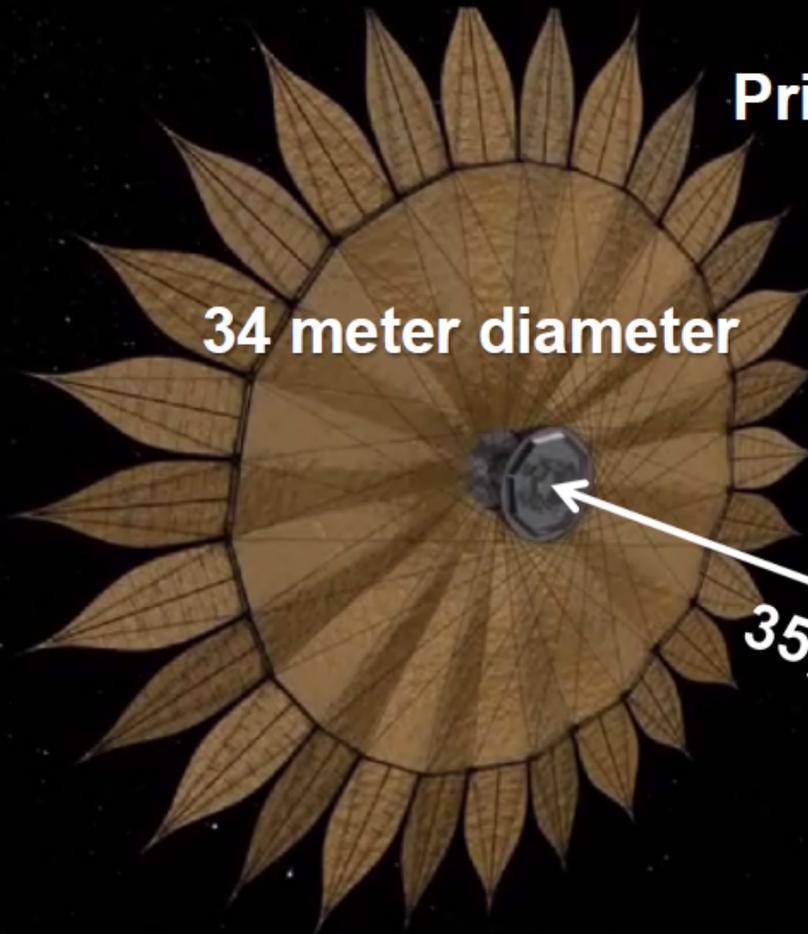
Image Post Processing



NASA, ESA, and R. Soummer (STScI)

Soummer et al. 2011

Starshade for a 2.4m telescope



34 meter diameter

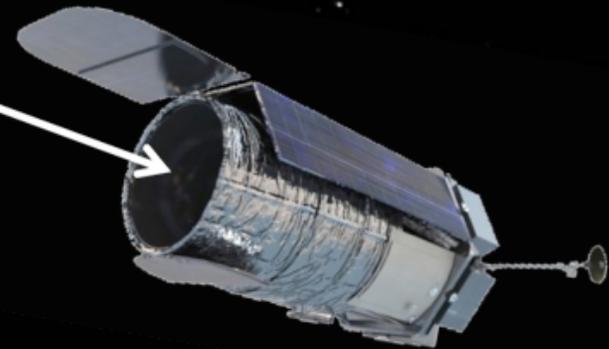
Primary bandpass: 600 – 850 nm

Raw contrast: 1×10^{-10}

IWA: 100 milliarcsec

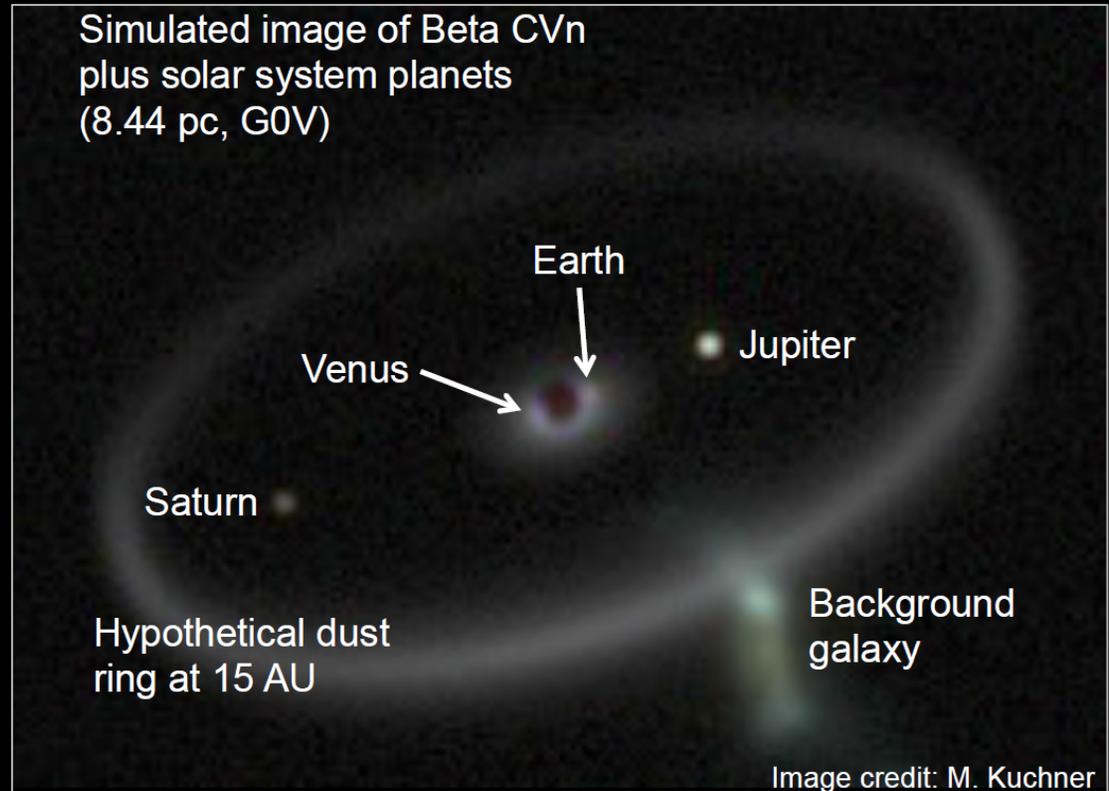
2.4 meter telescope

35,000 km



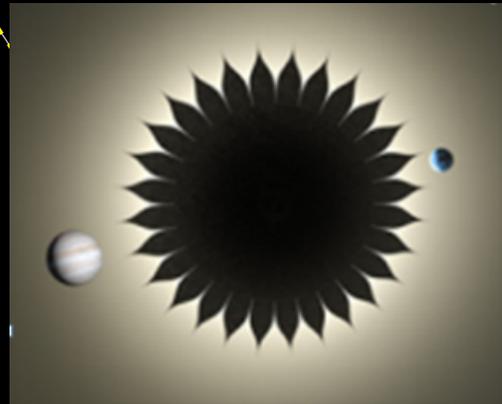
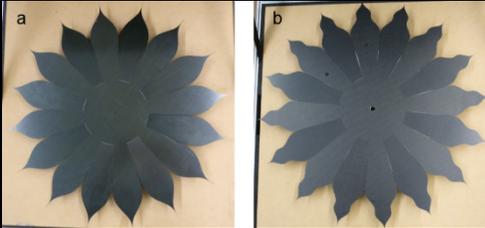
Example of Science from Starshade with 2.4m telescope

- Observe 52 stars in 2 years
- 13 known exoplanets
- 19 HZ targets. Expect ~ 2 Earths or Super-Earths
- Can detect sub-Neptunes to Jupiters around all HZ targets and 20 additional stars

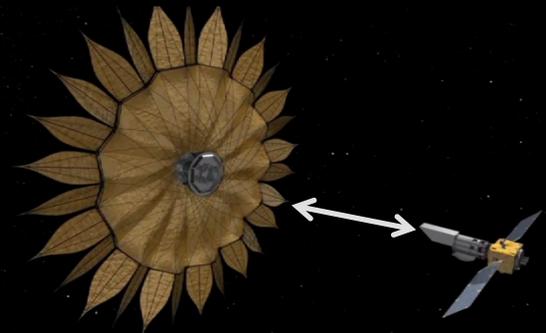


Technology Development for Starshades (External Occulters)

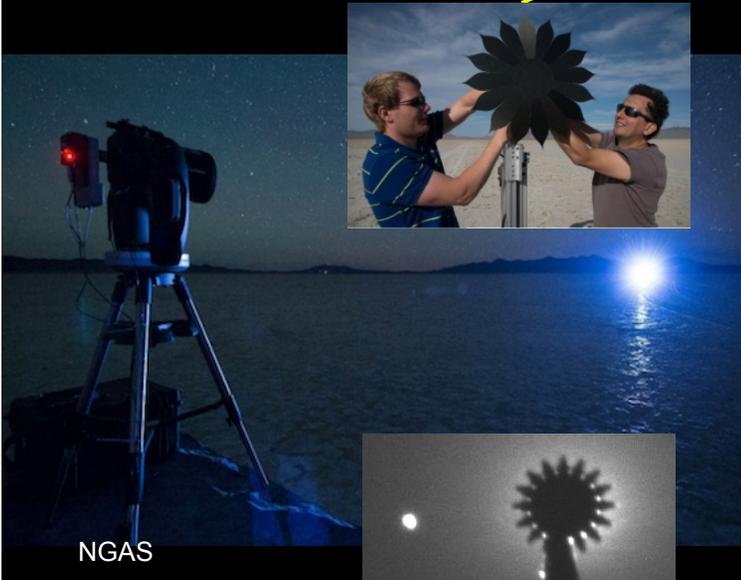
Control of Scattered Light



Formation Flying



Validation of Optical Models



NGAS

Starshade Deployment



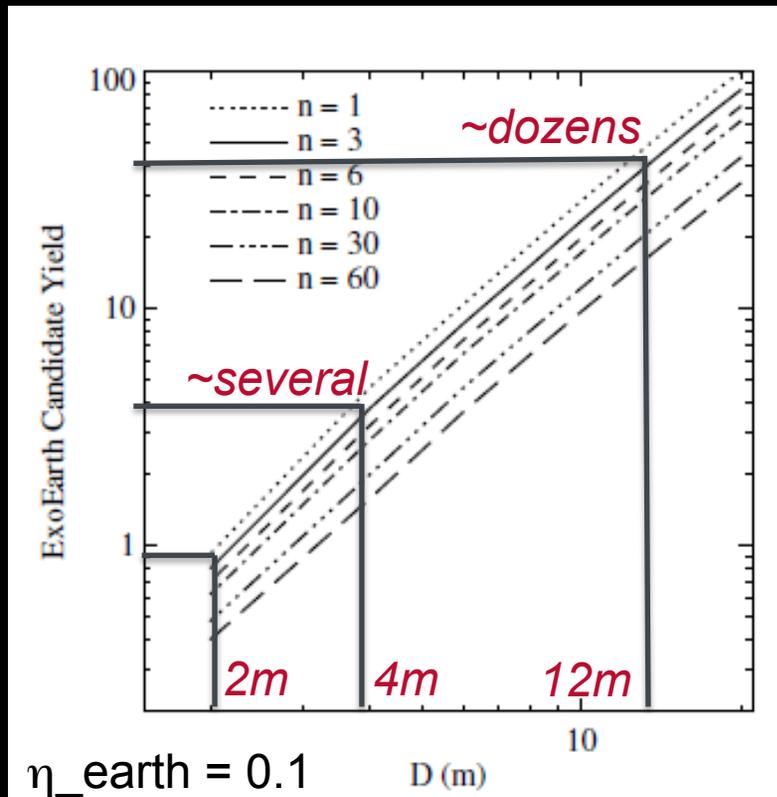
NGAS, Princeton, JPL

Petal Prototype



Princeton, JPL

Exo-Earths require large telescopes



Stark et al, 2014
For Coronagraphs

- Yield most sensitive to (in order):
 - Telescope diameter
 - Coronagraph inner working angle
 - Coronagraph contrast
 - Coronagraph noise floor
- Also sensitive to η_{earth} (strong) and exozodiacal dust (relatively weak)

Formative Era: Large UV-Optical-IR Telescope (LUVOIR)

Optics Deployment and Assy



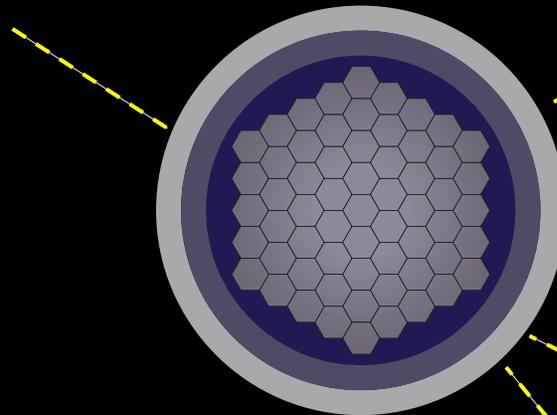
SiC Active Hybrid Mirror, Xinetics



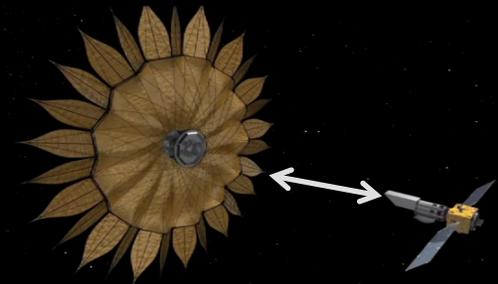
MOIRE, BATC



Lightweight ULE, ITT



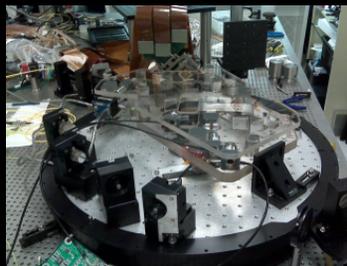
Formation Flying



Broadband Mirror Coatings

Telescope Mechanical Isolation Systems

Starlight Suppression Systems



Visible Nuller, GSFC



Pupil Mapping, Univ. Arizona



Starshade
NGAS, Princeton, JPL

The Program Address the Key Questions

Through Science, Advanced Studies, and Technology Development

1. Discovering Planets: How abundant are exoplanets in our Galaxy?

- Radial Velocity
- Transit Photometry
- Microlensing

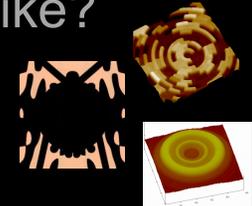
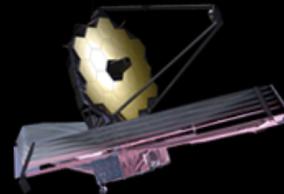
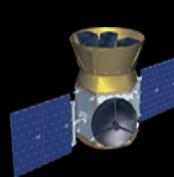


EPDS



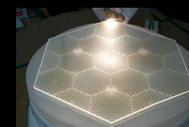
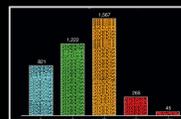
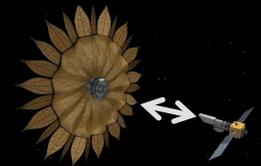
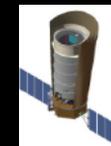
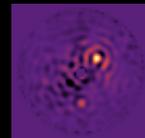
2. Characterizing Planets: What are the (large) exoplanets like?

- Transit Spectroscopy
- Direct Imaging



3. "Pale Blue Dots": Are the planets habitable? Are there signs of life?

- Transit Spectroscopy
- Direct Imaging
 - High Contrast
 - Small Inner Working Angle
 - Spectroscopy
 - η_{Earth}
 - Exozodiacal Dust
 - Yield

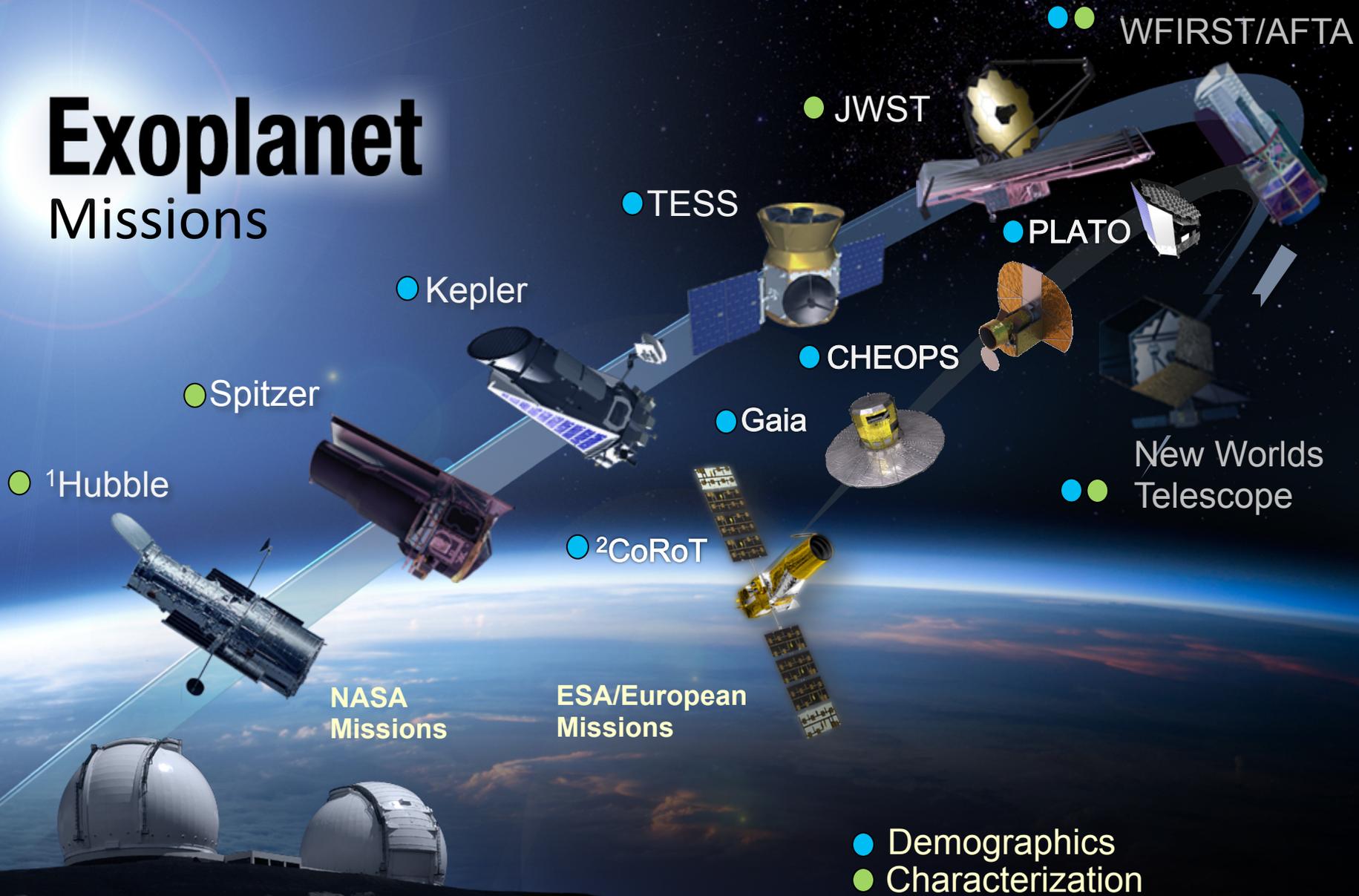


Ways to Become Involved

- ExoPAG: SAGs, and SIG
- EPDS initiative
- Program and decadal studies
- Competitive Funding:
 - Exoplanet Research Program (XRP) via ROSES
 - Astrophysics Data Analysis Program (ADAP, supports archival Kepler/K2 research)
 - K2 Guest Observer program
 - Astrophysics Theory Program (ATP)
 - Hubble Guest Observer program (supports exoplanet research)
 - SAT / TDEM (ROSES) for exoplanet technology development

Read more at: <http://exep.jpl.nasa.gov>

Exoplanet Missions



¹ NASA/ESA Partnership

² CNES/ESA



National Aeronautics and
Space Administration

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Pasadena, California

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